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Guide to Setting Thermal Comfort Criteria and Minimizing Energy Use in Delivering Thermal Comfort

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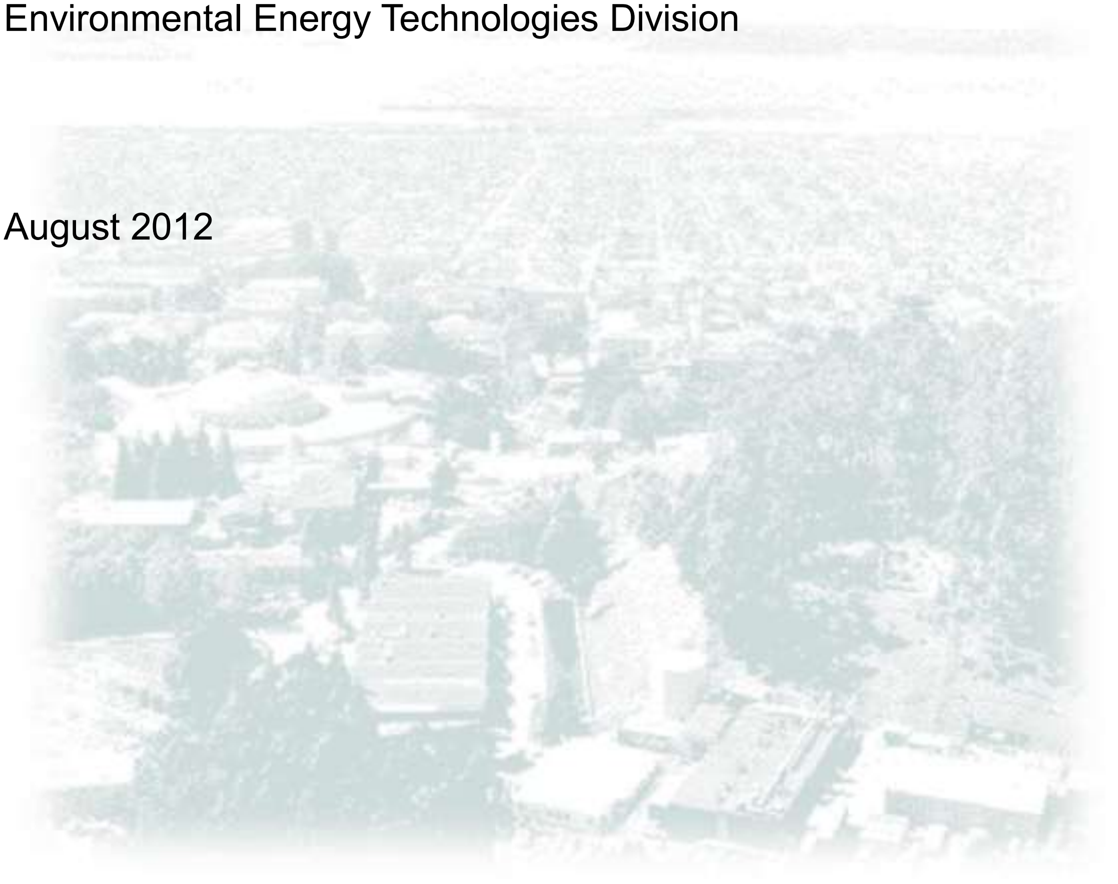

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Acknowledgments

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Guide to Setting Thermal Comfort Criteria and Minimizing Energy Use in Delivering Thermal Comfort

Who will find this document useful?

- **Building Designers**
- **Owners**
- **Operators**

INTRODUCTION

What is the purpose of this document?

Historically thermal comfort in buildings has been controlled by simple dry bulb temperature settings. As we move into more sophisticated low energy building systems that make use of alternate systems such as natural ventilation, mixed mode system and radiant thermal conditioning strategies, a more complete understanding of human comfort is needed for both design and control. This guide will support building designers, owners, operators and other stakeholders in defining quantifiable thermal comfort parameters—these can be used to support design, energy analysis and the evaluation of the thermal comfort benefits of design strategies. This guide also contains information that building owners and operators will find helpful for understanding the core concepts of thermal comfort. Whether for one building, or for a portfolio of buildings, this guide will also assist owners and designers in how to identify the mechanisms of thermal comfort and space conditioning strategies most important for their building and climate, and provide guidance towards low energy design options and operations that can successfully address thermal comfort. An example of low energy design options for thermal comfort is presented in some detail for cooling, while the fundamentals to follow a similar approach for heating are presented.

What are the benefits of setting thermal comfort criteria?

Space conditioning strategies have traditionally only emphasized the management of interior temperature and humidity conditions through mechanical conditioning systems to provide thermal comfort. Owners, operators and building designers may not typically understand or utilize the broader range of means at their disposal to support thermal comfort, or look to incorporate them into their designs or operation. Thoughtful building design that makes use of the wider array of available thermal comfort mechanisms and opportunities can be leveraged to result in significant energy savings, whether through operational improvements on an existing conditioning system or when evaluating options for a retrofit. In some climates, it may be possible to achieve thermal comfort through a different low energy space conditioning mechanism than would otherwise be considered, such as natural ventilation paired with localized air movement. In a case study at the University of Hawaii at Manoa, creating an “advanced” thermal comfort criteria that addressed their local climate demonstrated the viability of such a system, with predicted energy savings on the order of 60% over existing energy use. The information and methods outlined here aim to illustrate the value in setting thermal comfort criteria for a project and the array of opportunities it can present to benefit design and energy savings.

What is thermal comfort?

Thermal comfort is a subjective assessment by a person expressing their satisfaction with their local thermal environment. In practice, there are a number of variables that influence the body's heat balance with the environment, and in turn that person's perception of thermal comfort, including:

Personal Factors:

- Occupant activity
- Clothing

Environmental Factors:

- Air temperature
- Radiant temperature
- Air velocity
- Humidity

While these are the traditional, measurable factors that influence thermal comfort and are input variables into predictive models, it should be noted that there are many other factors that can affect either the body's heat balance, or their subjective response. As examples, these might include age, gender, health, culture, climate, season, personal control, past thermal history, and expectations.

Returning to the "classic 6" factors, however, the mechanisms that impact these factors are outlined in **Figure 1**. Heat transfer can occur by convection (air currents over the body, creating a cooling effect by inducing some evaporation over the skin), by conduction (contact heat transfer with other surfaces, e.g. flooring, furniture), by radiation (instantaneous infrared heat transfer with any visible object or surface at a different temperature than a person's body, e.g. the sun, the floor, the walls of a room), or by a person's biological processes (e.g. sweating, exhalation).

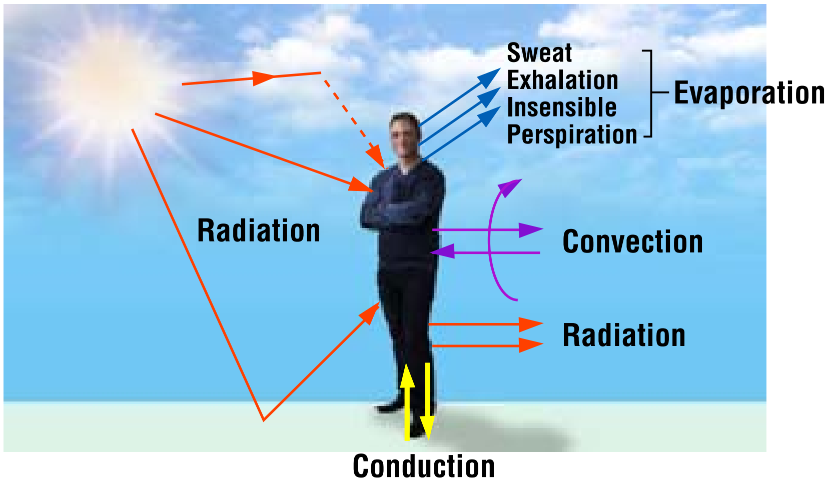

Figure 1: Components contributing to thermal comfort

Source: UC Berkeley Center for the Built Environment

Historically these factors have been taken into account in 'traditional' PMV or 'Predicted Mean Vote' thermal comfort, where a band of interior temperature and humidity ranges is prescribed to satisfy at least 80% of building occupants. This approach was developed in laboratory settings, where people were passive recipients of environmental stimuli and not connected visually or thermally to the outdoor environment, or provided with thermal controls in their environment (e.g. operable windows). For naturally ventilated spaces, where the occupant has access to and control of an operable window, the more recent adaptive thermal comfort regimen recognizes that a wider range of interior temperatures can be acceptable for occupants, particularly where occupants will adapt to changing exterior conditions and dress in accordance. In adaptive comfort conditions, interior temperatures vary to allow for slightly higher interior temperatures in the warmest periods of the year, and slightly cooler for cooler periods of the year. Both PMV and adaptive comfort criteria are described in further detail in ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55, "Thermal Environmental Conditions for Human Occupancy," a recognized industry standard providing guidance on thermal comfort parameters for building occupants. Today, PMV 'traditional' based comfort parameters are the primary option for buildings that use mechanical conditioning, while adaptive comfort conditions are allowed as an option for naturally ventilated systems. There is ongoing discussion in the research and standard-making communities about the applicability of the adaptive comfort zone for "mixed mode" buildings that utilize a combination of operable windows and mechanical cooling. ASHRAE Standard 55 also provides more detailed descriptions on the range of specific thermal comfort topics described throughout the remainder of this guide, and will be referred to as a relevant standard for the creation of thermal comfort criteria, with suggestions for further study not covered in the standard. For the purpose of this document 'advanced' thermal comfort criteria will include items such as those included in the 'Steps to Create Thermal Comfort Criteria'. Achieving thermal comfort for occupants is not a simple task; thermal comfort can be encouraged and improved upon however by paying attention to the physical factors that influence it. Energy efficient building design will take this a step further, paying attention to the most important thermal comfort mechanisms for a given climate and occupant activity, and selecting the lowest energy building systems to provide them.

Why are thermal comfort criteria important?

Providing a comfortable environment for occupants should be a high priority for a building—without this, the building may have higher lease turnover rates, disgruntled employees, increased lease transaction costs, higher maintenance calls and operational costs, as well as potential impacts on productivity. Establishing criteria for thermal comfort is an important tool to:

Set Goals:
Communicate clear thermal comfort expectations to all building stakeholders (facilities, occupants, management, design team)

Guide and Assess Design:
Provide a quantifiable means for assessing the thermal comfort success of a building design

Support Operations:
Guide building operators in how thermal comfort is delivered and can be improved in operation

How does the creation of thermal comfort criteria relate to energy savings?

Creating climate and building specific thermal comfort criteria will require a more thoughtful analysis of the local climate and the conditioning mechanisms that are best suited for it, which can help guide a design team towards the most energy efficient means to provide thermal comfort. Setting thermal comfort criteria helps the design team, owner and other stakeholders:

Identify most important mechanisms for delivering thermal comfort for a given climate

Identify lowest energy design and control options to support thermal comfort mechanisms

Evaluate and recommend low energy solutions

In one example of energy savings potential, Hoyt et al. (2009) conducted a series of annual energy use simulations for a prototype office building (4-stories, 124,000 sf) to investigate the energy savings of simply increasing the indoor cooling setpoint. They conducted this study in four climates: San Francisco, Miami, Phoenix, and Minneapolis. The predicted potential energy savings are substantial—compared to a baseline VAV reheat HVAC system with a cooling setpoint of 24°C (75.2°F), increasing the setpoint by 1°C to 25°C (77°F) resulted in predicted annual cooling energy savings of 7–15%, and increasing the setpoint by 2°C to 26°C (78.8°F) produced savings of 35–45% in all locations except Minneapolis. With attention to providing other means to improve thermal comfort, such as the adoption of a seasonal dress code or low-energy means for increasing air movement, a simple change in increasing the cooling setpoint in a facility can result in substantial energy savings.

Other energy benefits have been recognized through work conducted under the U.S. Department of Energy's Commercial Building Partnerships (CBP). As part of CBP, the University of Hawaii at Manoa developed thermal comfort criteria and used them to identify appropriate low energy cooling mechanisms for their climate, and as a result recognized greater energy savings. An energy simulation comparison showed significant energy savings of 25–37% over the energy use that would have resulted from using a 'traditional' approach and evaluation of thermal comfort, with the thermal comfort results helping to also prove the viability of a naturally ventilated retrofit. In general the energy benefits from creating thermal comfort criteria will vary, depending on the degree to which lower energy conditioning strategies will become viable for the building design and operations.

ENERGY SAVINGS FROM ATTENTION TO THERMAL COMFORT:
University of Hawaii at Manoa, Kuykendall Hall Retrofit

As part of the U.S. Department of Energy's Commercial Building Partnerships program (CBP) this project used their conceptual design stage to evaluate three different space cooling approaches for their building: fully sealed air-conditioned; mixed mode (combination of air conditioning and use of natural ventilation when possible); and naturally ventilated (included targeted, light dehumidification). For each of these options, UHM developed thermal comfort criteria and each option was evaluated for their potential energy savings and degree of thermal comfort.

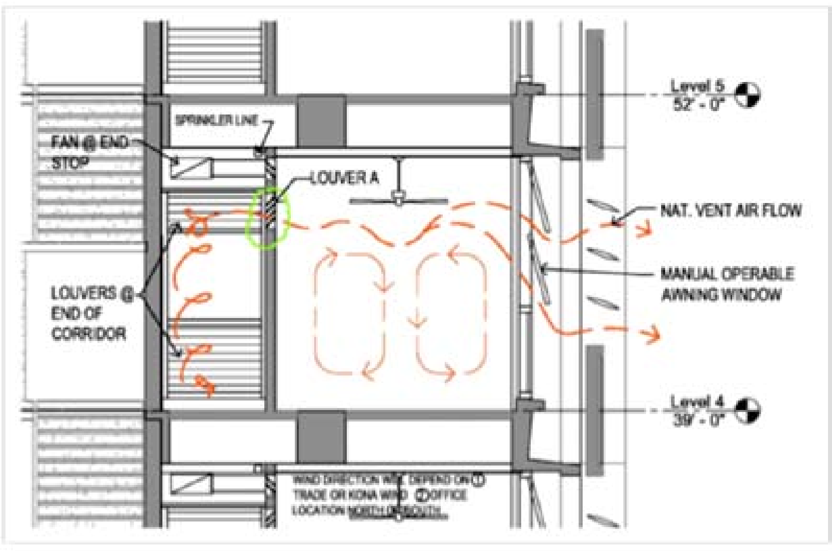

Figure 2: UHM, Kuykendall Hall example of natural ventilation, with fan system for nighttime dehumidification
Source: Ben Woo Architects

The thermal comfort criteria included the following items for the natural ventilation modes of operation:

- Accepted use of increased air movement to mitigate humidity effects and provide occupant cooling
- Accepted use of ASHRAE Std 55's adaptive thermal comfort interior temperature range, with an adjustment to the thermal range to account for the increased effects of local humidity on occupant

The process of creating the thermal comfort criteria required a detailed review of local climate conditions, which helped to illuminate several innovative design solutions:

- Enabled a viable natural ventilation design that took advantage of Hawaii's mild climate
- Provided a wider range of methods to provide occupant cooling, including use of ceiling fans and dehumidification of spaces at night to control humidity and moisture, rather than full air conditioning
- 'Transitional' spaces such as corridors were identified as areas where a wider range of temperatures was acceptable; these spaces were used to help reduce moisture on occupants before sitting in the naturally ventilated classrooms by using higher air movement rates to 'precool' occupants

As part of the process of setting thermal comfort criteria, some campus policies were reviewed and addressed, enabling low energy solutions when key 'buy-ins' from stakeholders were achieved:

- Acceptance of a greater interior temperature and humidity range
- Review of campus noise sources—design solutions and policies considered to reduce moped, leaf blower, skateboard and delivery noise sources, increasing viability of natural ventilation options

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- Institutionalization of occupant comfort as a key objective in their overall sustainability goals

To determine the energy benefits of developing the advanced thermal comfort criteria for the UHM project, an analysis was done to compare the performance of each conditioning option under the use of 'traditional' and the 'advanced' thermal comfort criteria. The results indicate a significant impact (see chart):

- Natural ventilation option—26% energy savings when 'advanced' thermal comfort criteria are used vs. 'traditional.' The use of advanced thermal comfort criteria, in particular inclusion of the adaptive comfort model, allowed natural ventilation to be viable for more occupied hours, reducing the energy use for this system. It should be noted that using the 'traditional' thermal comfort criteria, the natural ventilation option had an unacceptable number of hours when the interior space was outside the thermal comfort range, so additional thermal conditioning was triggered and reflected in this option's energy use.
- Mixed mode option—37% energy savings when the 'advanced' thermal comfort criteria was used vs. 'traditional.' The use of 'advanced' thermal comfort criteria for mixed mode allowed the natural ventilation portion of the mixed mode system to be enabled for a much greater number of occupied hours than with the 'traditional' thermal comfort criteria.

Overall the selected natural ventilation design, when using advanced thermal comfort criteria, showed 56% energy savings estimated over the existing building usage, with potential for a net-zero energy design with further development.

Aside from demonstrating energy savings, the analysis also indicated that with the use of 'advanced' thermal comfort criteria the natural ventilation option demonstrated acceptable levels of thermal comfort, whereas using 'traditional' thermal comfort criteria, the naturally ventilated option would not have captured all of the benefits of available conditioning strategies, and would not have indicated that thermal comfort was achievable. This option would not have been accepted as viable.

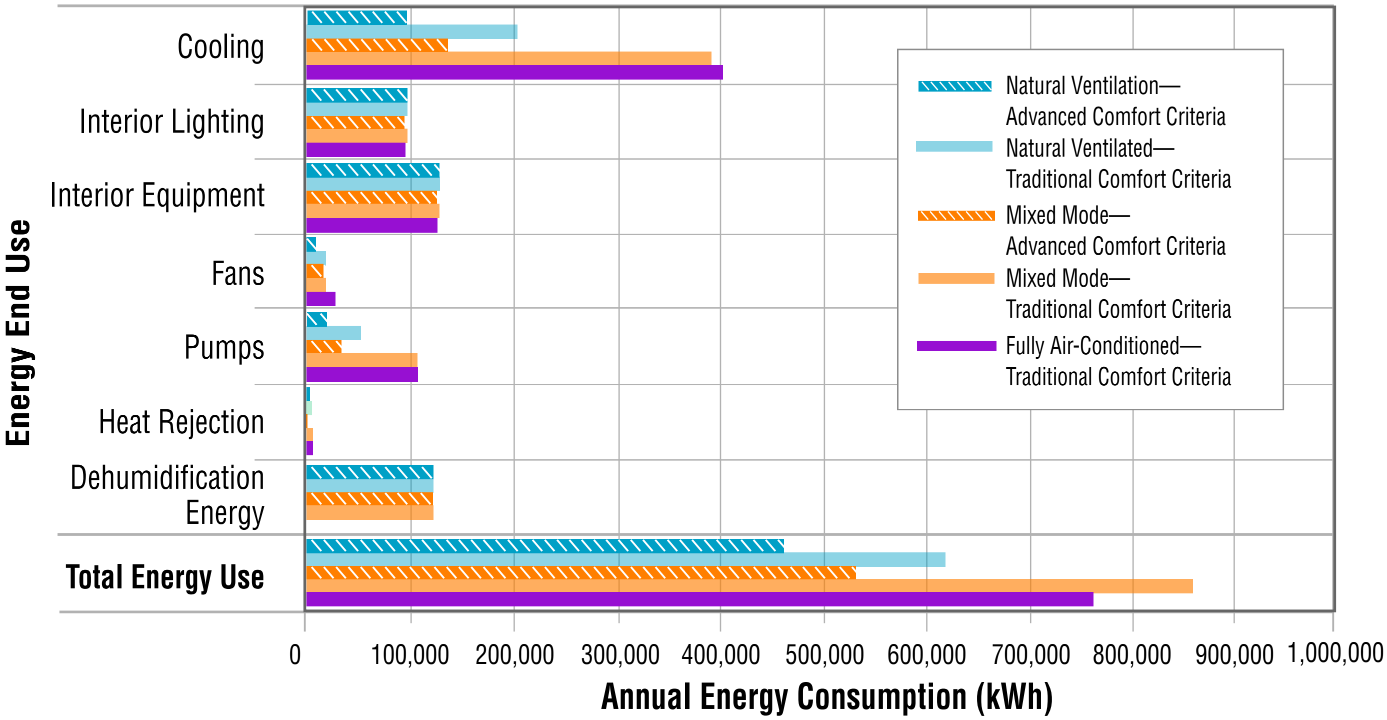


Figure 3: UHM Kuykendall Hall: Comparison of energy savings for different conditioning options using 'traditional' and 'advanced' thermal comfort criteria

Engaging and Educating Stakeholders

To identify, refine and adopt thermal comfort criteria, an owner should identify their key design and operational objectives, the different uses of the building, and engage with a thermal comfort expert, who could be part of their design team, to discuss and set the parameters for thermal comfort for each unique building use area. It will also be helpful to create thermal comfort standards for all potential different space conditioning modes—mechanical space conditioning, mixed mode conditioning or natural ventilation—if alternate modes will be viable design candidates, as the thermal comfort parameters will vary for each of these systems.

A thermal comfort expert should be responsible for providing the owner and other stakeholders with information that assists in their understanding of thermal comfort and enables informed decision making. The owner's responsibility lies in representing their corporate goals and objectives and assisting with the identification and engagement of other stakeholders where necessary.

Each of the stakeholder groups may require information or education related to thermal comfort:

- The variables that affect thermal comfort (both the classic 6 measurable factors, plus the more nuanced, subjective factors)
- How different design solutions support thermal comfort
- Descriptions of alternate space conditioning systems (mixed mode, natural ventilation, etc.), as needed to identify viability of systems as design solutions and determine the need to set thermal comfort criteria for each

Owner's Representative and Management

As an owner's representative, the key objectives are to provide clear direction on building goals and objectives to the team, and to enable decision making and adoption of the thermal comfort criteria.

- Provide leadership in setting and adoption of thermal comfort criteria
- Identify owner design objectives and goals
- Engage and through dialogue work towards buy-in with all stakeholders

Key Issues

While discussing thermal comfort criteria for different space conditioning strategies, less conventional systems such as mixed mode or natural ventilation may present some issues for management or facilities personnel. It will be useful to provide education on how these systems operate, provide thermal comfort, and examples of how these systems have operated successfully. Having thermal comfort criteria for all of these space conditioning modes will allow comprehensive evaluation of all strategies, including cost, energy and thermal comfort analysis, which will also help frame a broader discussion of the merits and risks of such systems before adoption.

Occupants and Occupants’ Representative

Whether the thermal comfort criteria are being set for use in a single building, or for the creation of a standard for a portfolio of buildings, it is important to consider feedback from the occupants of the building(s). Engaging with the occupants’ representative will provide a communication bridge with the group ultimately affected by the implemented design solutions. The ‘advanced’ thermal comfort criteria may also include a process to ensure that occupant groups are engaged in the design process, to provide feedback during the process of making plans for retrofit work, or to provide post-occupancy evaluations of performance after such work is done. One mechanism that allows for a rich amount of occupant input is the use of an occupant survey.

A post-occupancy survey, whether for a retrofit or new construction project, provides several benefits:

- Determines occupant satisfaction
- Measures effectiveness of system relative to thermal comfort design intent
- Identifies post-construction issues to remedy while under warranty

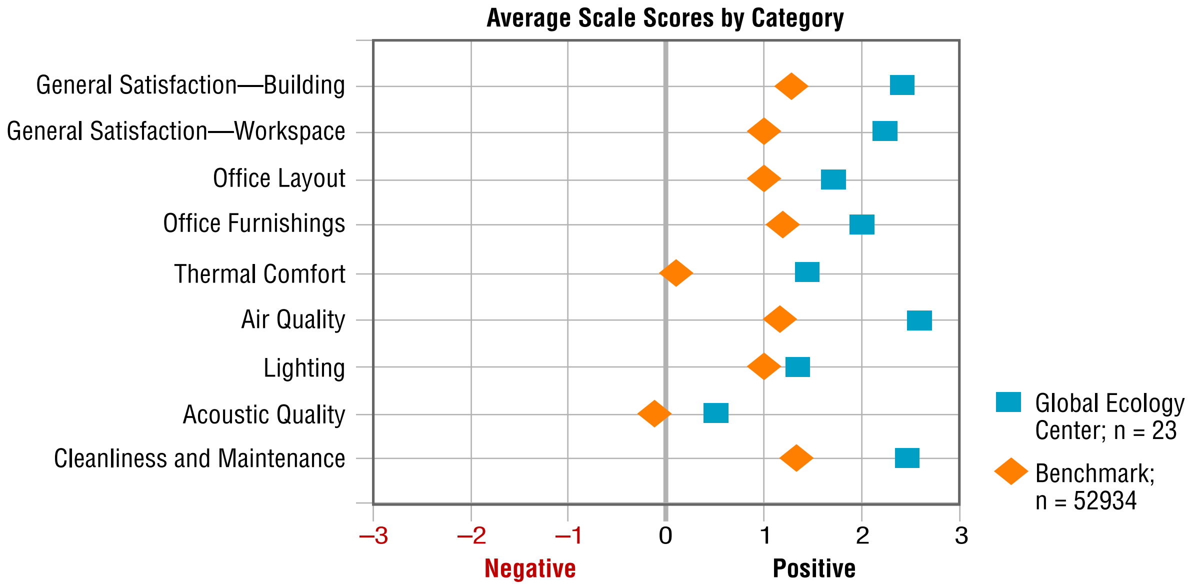


Figure 4: Sample Post-Occupancy Evaluation Survey Results Summary

Source: U.C. Berkeley Center for the Built Environment

If done prior to a retrofit or new construction, such a survey also:

- Affirms importance of occupant engagement role in design process
- Identifies key existing performance issues experienced by the occupants in their current space, which might inform the design process
- Helps to identify priorities for investments for improving operations
- Helps to identify any barriers in operations to design solutions

When a post-occupancy survey is used both before and after retrofits to an existing space, or a move to a new building, then the comparison of those two sets of survey results can be especially informative.

Key Issues

Occupant surveys should target a high response rate for a representative sample of the building(s). Also consider completing surveys at six month intervals in order to recognize and address seasonal performance issues.

Building Operators

Building operators are key stakeholders in defining thermal comfort criteria. Their understanding and buy in are essential in both enabling low energy design options in a building, and in maintaining energy performance after construction. As part of the thermal comfort criteria discussion, be sure to educate and address any issues, especially as they may relate to any unique thermal conditioning systems (e.g. mixed mode, natural ventilation, use of localized conditioning, etc.). Important areas to address with these stakeholders and management may include:

- Maintenance issues—e.g., new technologies, training needs, etc.
- Controls issues—e.g., occupant controls, adjustments to controls, etc.
- Security concerns (e.g. with operable windows)
- Other concerns with different space conditioning mechanisms

Key Issues

Each of these concerns may have multiple solutions, whether through design or policy. However they cannot be understood and addressed without the key engagement of operational staff.

Steps to Create Thermal Comfort Criteria

1. **Engage a thermal comfort expert**—This may be a person on your design team, or a separate contractor. This person will help ensure that all thermal comfort variables are addressed in the criteria, and help provide guidance and education on thermal comfort issues.

2. **Define spaces of distinct thermal comfort needs**—Thermal comfort criteria should be defined for each of these distinct cases. Possible divisions could include:

   a. Occupancy periods (e.g. regularly occupied, 'transitional spaces' (see Sidebar: "Transitional Spaces" on Page 9), non-occupied spaces, etc.)

   b. Different occupant exertion areas (e.g. areas of sedentary activities, areas where physical exercise occurs, etc.)

3. **Select wind and weather data source**— Identify the weather and wind data sources to be used as a basis for design and operations. Ideally this would be historic data collected on site, to capture localized weather and wind patterns, or if not available identify a suitable local weather and wind station, potentially with some guidance on adjustments to be made with collected data to more accurately reflect local conditions. Select a source with reliable, multi-year data available (ideally no less than 5 years worth of data) with an environmental condition as similar to the site as possible, including local wind patterns.

4. **Select reference thermal comfort standards as a baseline**—ASHRAE Standard 55 may be appropriate for most cases, while recognizing that there are a variety of guidelines even within that single standard (i.e., adaptive comfort zone, elevated air movement, local asymmetry, etc.). In some cases, published papers or international standards might be drawn upon to provide additional guidance.

TRANSITIONAL SPACES: An Opportunity for Energy Reduction

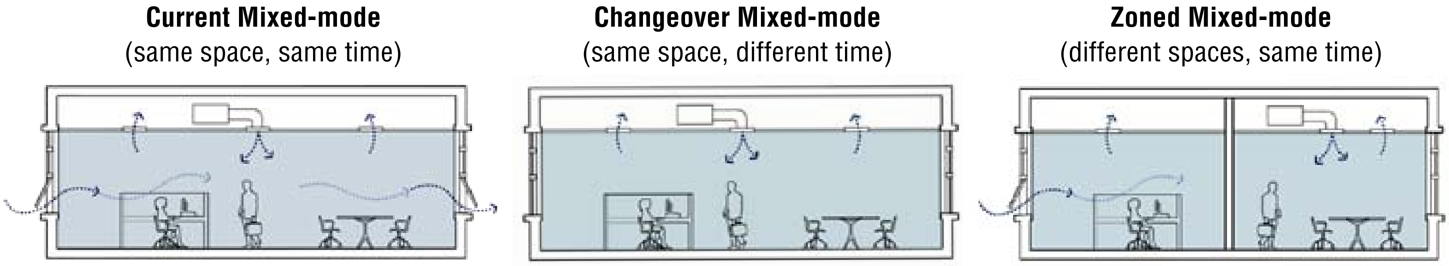
It may be beneficial to separately recognize the thermal comfort requirements for transitional spaces, spaces that are occupied for short periods of time such as corridors and lobbies. ASHRAE Standard 55-2010 does not currently provide specific guidance for these areas. The following may be useful as a starting point for discussions:

- Define areas this applies to, e.g. may include building entrances, exits, corridors and other transient common areas
- Set an occupancy definition, e.g. may be spaces occupied continuously by an occupant for 15 minutes or less

Possible thermal comfort criteria and design solutions may include:

- Consider an increase in range of acceptable temperatures, e.g. up to 86^{o}F, perhaps when coupled with a requirement for increased air speed
- Evaluate viability of using substantial air movement and dehumidification (if required) to eliminate mechanical air conditioning
- When necessary, use mechanical systems to provide cooling. Capacity and hours of operation may be minimized to provide minimum temperature and humidity control during desired hours or conditions (e.g. exterior doors opening and closing)
- If there are only a few regular occupants in an otherwise transitional space (e.g. security guards in a lobby), consider local means of providing comfort for these occupants. Emphasize conditioning strategies that directly influence the occupant area, e.g. personal fans, local radiant system for heating, etc.

5 **Define the conditioning systems to be addressed with the thermal comfort criteria**—Options may include mechanical conditioning, natural ventilation, and mixed mode systems which employ the use of natural ventilation when possible, with a backup air conditioning system. A well-designed mixed-mode building begins with intelligent facade design to minimize cooling loads. It then integrates the use of air-conditioning when and where it is necessary, with the use of natural ventilation whenever it is feasible or desirable, to maximize comfort while avoiding the significant energy use and operating costs of year-round air conditioning. There does not seem to be a “standard” mixed-mode approach in practice today—each building continues to be unique. Yet there are a number of classification schemes that describe the integration of natural ventilation and air-conditioning control strategies, usually in terms of whether they exist in the same space, or operate at the same time.


Current Mixed-mode
(same space, same time)

Changeover Mixed-mode
(same space, different time)

Zoned Mixed-mode
(different spaces, same time)

Figure 5: Example of mixed-mode conditioning

Source: : UC Berkeley Center for the Built Environment

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6 **Define the thermal comfort criteria associated with the different modes of the conditioning system** —Thermal comfort criteria will vary in each of the different modes of operation of these systems. If you have a zoned mixed-mode system, the PMV-based and adaptive-based comfort zones might be most easily applied to the conditioned and naturally ventilated spaces, respectively. For the changeover systems, you might need to specify the thermal comfort parameters for each of the three modes of control: mechanical cooling mode, natural ventilation mode, and the transitional mode where the system shifts between mechanical and natural ventilation. The concurrent system is more complicated, and probably depends on how extensively the windows are used. An industry standard currently does not exist for mixed mode buildings, making a discussion with stakeholders essential to clearly define the thermal comfort criteria and modes of operation. The owner and design team may look towards existing standards for adaptive comfort (for natural ventilation) and ASHRAE Std 55's traditional comfort zone for sealed buildings as a starting place.

7 **Set interior environmental conditions for comfort**—For each distinct thermal comfort case, and space conditioning system, define the temperature and humidity ranges acceptable for thermal comfort. ASHRAE Std 55's PMV 'traditional' thermal comfort parameters may be referred to for mechanically conditioned spaces; the ASHRAE Std 55 adaptive comfort model may be the appropriate reference for naturally ventilated modes of operation. See '*Mixed Mode Systems*' sidebar below for mixed-mode buildings.

8 **Determine if alterations to reference standards are applicable**—In reviewing the reference standards for a particular climate, site or use, some alterations might be worth considering where the standard does not accurately reflect the site conditions or use of the space. For example the adaptive comfort model in ASHRAE Standard 55 uses mean monthly average outdoor dry bulb temperatures to determine the applicable interior acceptable temperature range. If local data is available, and a review of the climate data indicates weather patterns that this approach would artificially discount, it may be worth considering using a smaller timeframe to set interior temperature ranges for thermal comfort. Weekly outdoor temperature data for example, might do a better job of recognizing the impacts of short term 'heat waves', whereas monthly averaged data may not. (As of this writing, changes are underway in Std 55 that would allow for a running mean outdoor temperature as the independent variable).

MIXED MODE SYSTEMS: Controls Strategies For Consideration

Mixed mode systems are not specifically addressed in ASHRAE Std 55, although some of their modes of operation will relate to the comfort parameters described in the standard (e.g. natural ventilation mode may relate to the adaptive comfort standard, whereas full mechanical conditioning mode may relate to the 'traditional PMV' ASHRAE thermal comfort standards). It is highly recommended to engage in discussions with all building stakeholders—management, facilities and the occupants—to discuss, and adopt a recommended approach to the thermal comfort controls for this system. Sample controls strategies may include:

1. **Conventional/Conservative:** Use 'sealed, mechanically conditioned' thermal comfort PMV-based criteria in all modes of operation—Operation of the building as if it were entirely dependent on mechanical conditioning, where the mechanical system is continuously active and where windows are seen as an amenity, not a primary means of thermal control.

2. **Conventional/Relaxed:** Similar to the "Conventional/Conservative" strategy, but allowing wider deadbands in all modes of operation.

3. **Adaptive/Ramped:** Employs adaptive comfort criteria during natural ventilation mode. During a transitional period of engaging a mechanical conditioning mode, control setpoints will be at the upper temperature limits of the adaptive comfort range (for cooling). For extended periods of mechanical cooling, 'sealed, mechanically conditioned' thermal comfort criteria would be observed.

4. **Adaptive/Conserving:** Utilize adaptive thermal criteria throughout all modes of operation. Mechanical system operation is solely used to supplement natural ventilation as needed to maintain temperatures under the maximum adaptive thermal comfort limit.

9 **Determine whether local humidity effects require special consideration**—For humid climates using naturally ventilated modes of operation, it may be prudent to assess whether local humidity ranges are well represented in the standards being considered for use. ASHRAE Std 55's adaptive comfort criteria makes uses of a mean monthly outdoor dry bulb temperature to assess what the interior temperature range should be for thermal comfort. For humid climates, it may not be the most accurate overall representation of exterior conditions to only rely on exterior dry bulb temperatures alone—when higher humidity occurs, otherwise mild temperatures can feel warmer. One way to address this is to make use of the mean outdoor effective temperature, ET*(de Dear and Brager 1998), which combines temperature and humidity into a single index, similar to the wind chill metric. ET*is defined as the temperature at 50% relative humidity which would cause the same sensible plus latent heat exchange from a person as would the actual environment. Two environments with the same ET* should provide the same thermal response even though they have different temperatures and humidities, as long as they have the same air velocities. Effective temperatures (ET*) may be calculated with the ASHRAE Thermal Comfort Tool CD, Version 2 (2011, by Charlie Huizenga), available from the online ASHRAE Bookstore (http://www.techstreet.com/cgi-bin/detail?product_id=1806669). ET* could be used in place of the outdoor dry bulb temperatures used in the adaptive comfort model with adjustments (de Dear and Brager 1998), to provide a closer approximation of the local effects of humidity on the space, and was the basis for the original analysis.

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10 **Set an occupant clothing value**—For each distinct thermal comfort criteria case, state the assumption of the clothing level of the occupants. Clothing (clo) values are typically between 0.5 and 1.2. ASHRAE Standard 55 may be referenced for furher information, including guidance in calculating clothing values on the basis of activity type and duration.

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11 **Assess and define seasonal considerations**—Provide any direction on differences in clothing values appropriate for seasonal change, use changes of spaces that vary seasonally (such as occupancy reduction in summer) or any other seasonal considerations.

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12 **Set occupant control standards**—Define what types of occupant control over thermal comfort are desired and are acceptable, and any operational or design restrictions on these controls (e.g. maximum opening area of operable windows for security purposes). This information will help provide design teams and operators with options to improve thermal comfort at the occupant level. Choices include:

a. Personal fans

b. Operable window control (manual or automatic)

c. Thermostats

d. Local mechanical fans (ceiling fans, desk fans, etc.)

e. Shading or glare control devices (internal or external)

f. Other devices

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13 **Define minimum coverage of occupant controls**—ASHRAE Std 55 provides some guidance in this area, to be adjusted as necessary. State minimum density of occupant controls (e.g. one operable device per occupant, whether at perimeter or interior space), for each type of permitted control (e.g. thermostats, operable windows, ceiling fans, etc.).

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14 **Include occupant education requirements**—Define means by which occupants will be educated about the use of their environmental controls. A written description may be considered along with a means of disseminating the information.

15 **Set a thermal comfort acceptability standard**—For spaces following the 'traditional' thermal comfort criteria outline in ASHRAE Std 55, these criteria are developed for 80% occupant acceptability of thermal comfort. For spaces following the adaptive thermal comfort model in ASHRAE Std 55, two acceptability ranges are provided, 80% and 90% acceptability, where 80% is the typical recommendation, and the 90% criteria may apply for conditions where a tighter range of interior temperatures is desired.

16 **Set a number of acceptable allowable hours of exceedence**—In designing system options, the thermal comfort analysis may indicate that a system performs very well, except for a small range of hours, perhaps coinciding with an annual extreme weather event. A small percentage of hours out of the acceptability range may be permissible by the owner, e.g., 3-5% of working hours, and should be discussed. Consider also whether the exceedence hours should be set for only occupied hours, or if a separate standard could apply for unoccupied hours.

17 **Describe any design elements desired**—For each conditioning system, identify whether any level of controls or design elements is desired in the system to allow for flexibility in operations in future. Particularly for systems that will be new to the owner and operators, a certain level of controls flexibility, system switchover or redundancy, may be desired to help tune the system once in operation. Refer to the '*Mixed Mode*' sample sidebar (Page 10) for an illustrative example, where some flexibility in system controls may be desired, to allow for an alternate transitional mode controls strategy to be engaged.

18 **Set a standard for use of occupant surveys**—Pre-retrofit and post-construction surveys can be exceptionally valuable tools for identifying existing thermal comfort problems, and point towards design or operational solutions.   Determine timing and frequency of conducting surveys.

THERMAL COMFORT CRITERIA AND LOW ENERGY DESIGN

How can setting thermal comfort criteria help to inform building systems choices?

The process of setting thermal comfort criteria will require an evaluation of local climate conditions. In evaluation of the local climate, an understanding of the primary climatic challenges for thermal comfort will emerge, and design strategies to mitigate them may assist in the identification of low energy building conditioning systems. Low energy means to improve occupant comfort, at the occupant level, will also be identified.

For example, for a temperate humid environment it may be possible to design a system with low enough internal loads and an emphasis on air movement, whether through natural ventilation or via mechanically assisted ventilation, such as local mechanical devices (e.g. ceiling or desk fans), that could meet all or most of the space cooling needs. This would be a dramatic energy savings over a system that provided full space air-conditioning, such as in the UHM case where this scenario is achieving 40% energy savings for the naturally ventilated design over the fully sealed, air conditioned design.

Some low energy, low impact design principles for thermal comfort are outlined below and illustrate the link between thermal comfort variables and low energy conditioning technologies. For all of the following suggestions, an analysis should be done to ensure that the strategy will result in energy savings over alternative strategies.

For cooling benefits:

- Reduce or eliminate warm radiative surfaces, particularly warm ceilings, but also warm vertical surfaces, and to a lesser degree warm floors
- Reduce or eliminate direct solar gain onto occupants
- Provide means for occupant to adjust solar gain into space (e.g. exterior shading, internal blinds)
- Provide elevated air movement to occupants, in occupied zone, e.g. by personal fan or ceiling fan
- Provide low-energy personal environmental controls (e.g. operable windows, fans); air movement directed near the head area is the most effective use of local control
- Address humidity and sensible cooling loads separately
- Assess whether thermal comfort can be controlled by relatively low amounts of air movement alone rather than actively controlling interior humidity levels
- Identify if there are significant diurnal swings in dry-bulb and/or wet-bulb temperatures—if so, look at night time stored cooling strategies to capitalize on the swings
- Consider use of thermal mass to store "coolth"
- Consider use of radiative cooling sources, at occupied level (e.g. in-slab radiant cooling, radiant cooling panels etc.), paying attention to interior dewpoint conditions to eliminate condensation potential
- Evaluate local climate data for natural ventilation cooling potential, including wind speed and humidity considerations; thermal comfort criteria will identify viability of operable windows, opening areas and controls permissible to evaluate natural ventilation potential

For heating benefits:

- Reduce or eliminate drafts
- Reduce or eliminate cold radiative surfaces, particularly cold floors, but also cool vertical surfaces and ceilings (e.g. single pane windows, metal framed windows, uninsulated thermally massive walls (e.g. brick or concrete)
- Reduce stratification in space—provide heating at the occupied level, avoid air-based heating systems in high ceiling areas
- Provide personal environmental controls, providing heat to the foot area is the most effective use of local control
- Consider use of radiative heating sources, at occupied level (e.g. in-slab radiant heating, radiant heating panels, etc.)

Other factors to consider that might contribute to occupant discomfort include swings in temperature, or a rapid increase or decrease in space temperature over time in a space due to effects not in the occupants' control, such as mechanical system performance.

A general strategy for identifying viable low energy cooling strategies is suggested by the following chart for various climate types. A similar process could be followed for heating strategies, prioritizing strategies that provide heating benefits most relevant for a given climate condition. In general, for greatest energy benefits, prioritize thermal comfort strategies that improve interior conditions first, such as reducing radiant asymmetry and reducing draft. Then make best use of available natural ventilation, occupant controls and personal fans or other devices to improve comfort conditions before relying on mechanical systems to condition a space. Other measures, such as a seasonally variable dress code may also be employed to improve the viability of the proposed systems.

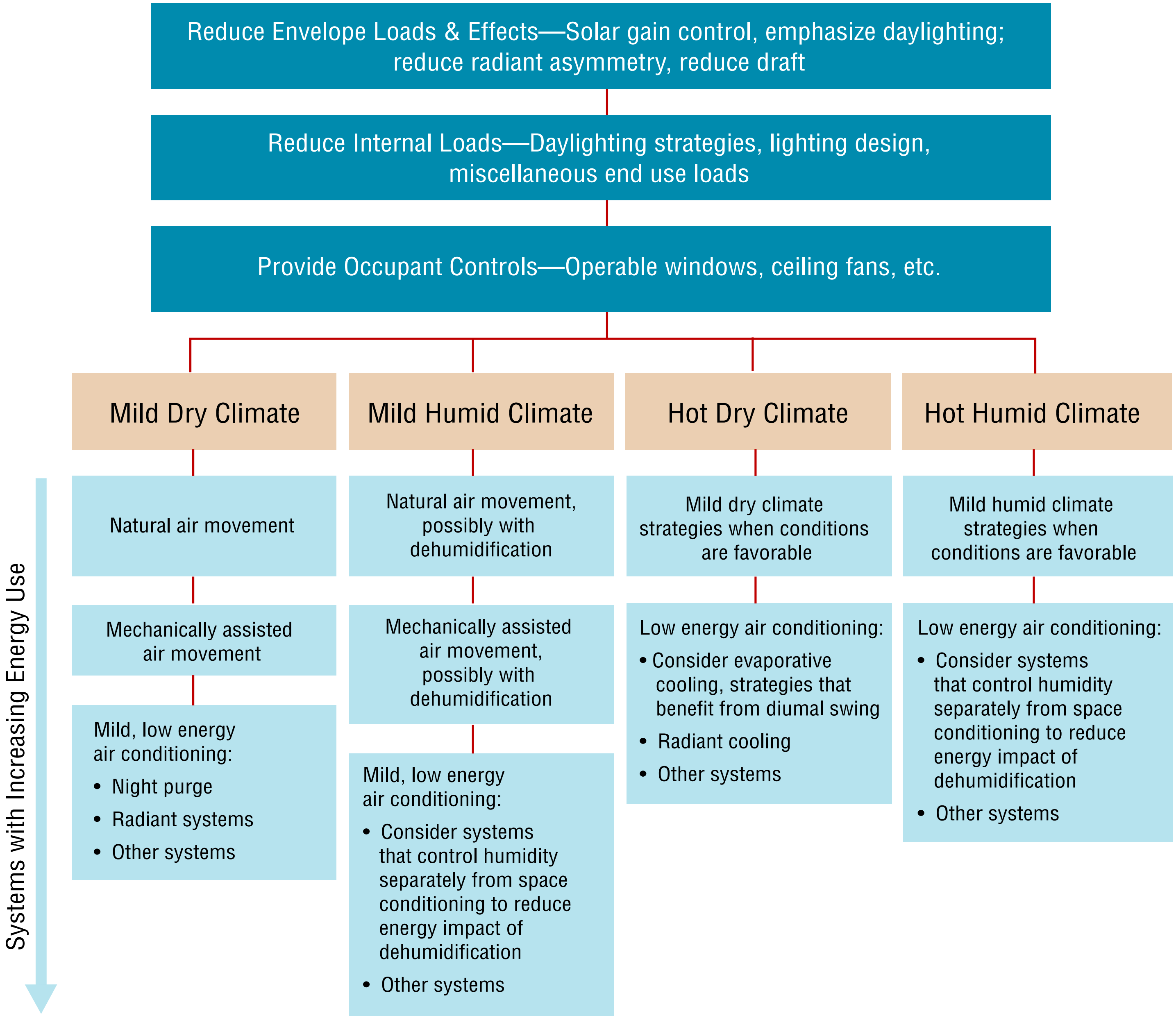

Figure 6: Low energy cooling strategy considerations for thermal comfort in various climate types

When mechanical cooling systems must be considered however, they should be selected carefully for their given environment, and understood for their benefits and potential challenges for providing thermal comfort. Air-based delivery systems can be provided at a relatively low energy design, or conversely they can be designed as some of the most energy consuming conditioning systems. Careful consideration of the design of these systems is advised.

Some other considerations for air-based conditioning systems include:

- Mainly conditions space to a dry-bulb temperature setpoint
- May over-dehumidify or overcool air, especially where refrigerant-based systems are used, sometimes requiring reheating of the air supply, increasing energy use
- Provides occupants with limited control of their thermal environment via occasional thermostats

- Continually cycle to reach the desired set point
- Drafts may be more of an issue, with cold air ‘dumping’ onto occupants if not considered in design
- Generally have potential for a high energy intensity

Systems utilizing radiant surfaces or panels to condition a space can be effective low energy space conditioning alternatives. Some considerations for these kinds of systems include:

- They can be effective at reducing temperature asymmetry
- Limited cooling capacity, requires aggressive low energy envelope and interior loads design
- Requires attention to interior dewpoint to avoid condensation for cooling
- Their operating characteristics may result in low energy use
  - Low pump and fan power
  - Near-ambient flow temperatures
  - Use ‘free’ cooling techniques such as ‘charging’ of surfaces with cool night air or using cooling tower water, or ground source heat pumps to cool floor/ ceiling slabs

ANALYZING THERMAL COMFORT IN DESIGN AND OPERATIONS

Once the thermal comfort criteria have been defined, the design team will need to provide an assessment of the relative thermal comfort performance of different design options. The following methodology can also be used by building operators to assess the success of a building reaching its thermal comfort goals. With the thermal comfort criteria, it is likely that some of the criteria can be input into available energy simulation tools, while other criteria cannot be. In these cases, it will be most useful for the design team to set up a spreadsheet to post-process the annual energy use and interior condition data to adjust for the factors that were not able to be implemented through the model. In many cases this may be a straight-forward operation.

Analysis of Thermal Comfort Data

Many annual energy analysis software programs and operations energy management systems allow for the export of interior space temperatures.

- Create a spreadsheet to import and manage data, including interior conditions by zone and outdoor conditions, for all hours of the year
- Pick key thermal zones for review (e.g. samples of south facing, western exposure, eastern, interior core space, etc.)
- Use the thermal comfort criteria defined as bounds on acceptable interior space temps
- Some annual energy analysis software may not capture the comfort benefits of all design solutions, post processing of interior temperature data may be necessary, e.g.:
  - Benefit of elevated air speed at occupant (several degrees worth of cooling benefit)
  - Relationship to mean outdoor temperature, or effective temperature ET*
- Color-code conditions that are small degrees (e.g.1–2^{o}F) or more outside of comfort range—quantify these hours, compare against the acceptable hours of exceedence. Some amount of temperature exceedence may be acceptable to owner, and should be reviewed with them
- Utilize charts or scatterplots to illustrate thermal performance
- Consider having several thermal comfort results shown to demonstrate the effectiveness of various design strategies, e.g. with and without ceiling fan control

Visualizing Thermal Comfort

With a large amount of processed data, it is essential to be able to demonstrate the thermal comfort results in a simple and effective manner to determine whether issues exist, and to what degree. One effective graphical option, utilized on the University of Hawaii project, uses a heat map of interior conditions, shown in **Figure 7**. This illustrates thermal comfort performance for every hour of every day of the year with temperature conditions color coded to represent areas when conditions are within the thermal comfort criteria, and when they are marginally, or greatly, outside of these bounds.

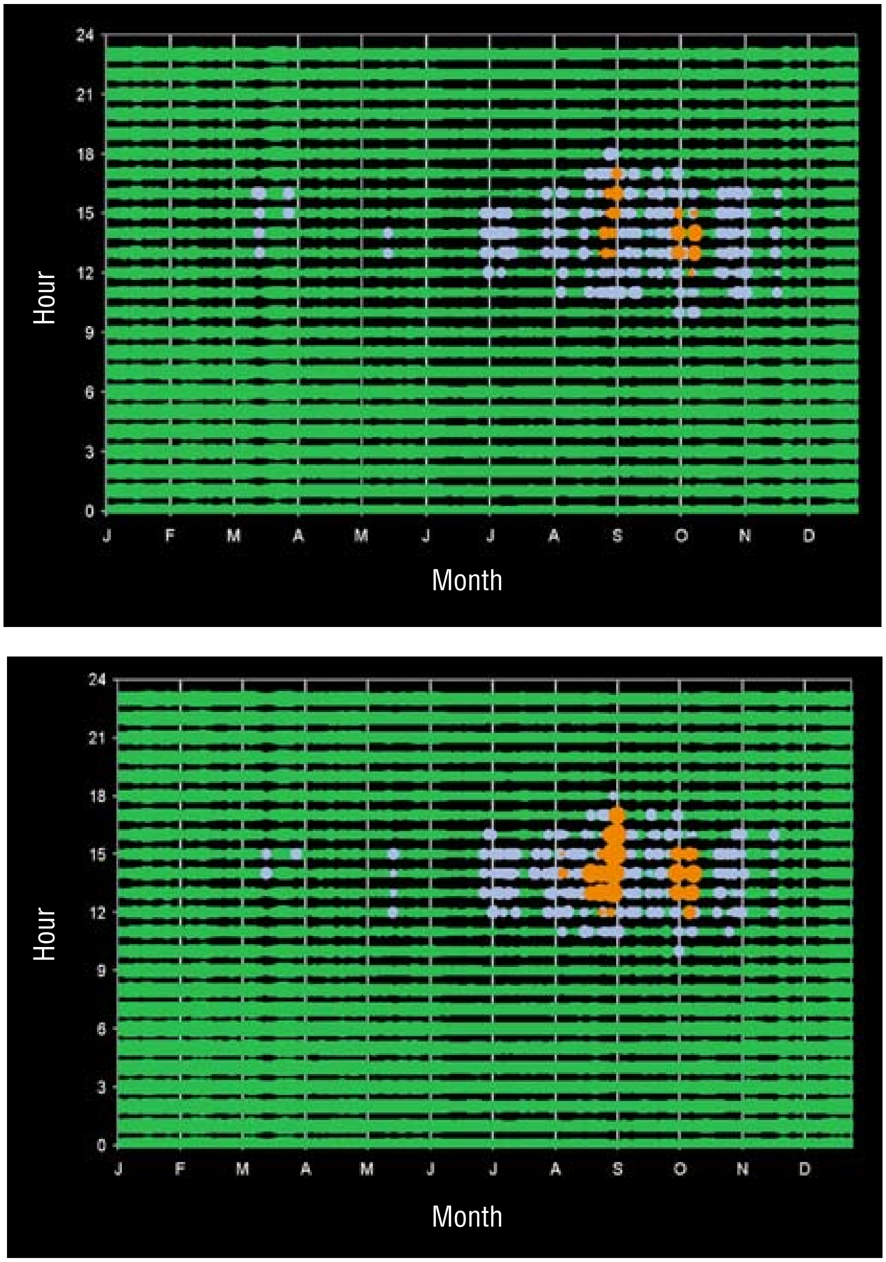

Figure 7: Thermal Comfort Performance Results

Source: Loisos and Ubbelohde Architects

ENSURING SUCCESS

Developing thermal comfort criteria for a building or campus can be done quickly and with great benefit to organizational operations and practices. Some organizational barriers may arise during the process, which effectively present opportunities to incorporate successful energy efficiency at a deeper level in the organization. To ensure a successful process developing thermal comfort criteria:

- Start discussions before design starts
- Engage all stakeholders
- Expect some educating will be needed
- Document the process and the results
- Keep the thermal comfort criteria as a living document throughout operations

An investment in defining the thermal comfort criteria for a building or campus will provide long term value both in design and long after in maintaining low energy operations that also provide thermal comfort to occupants.

RESOURCES

ASHRAE (2010). *ANSI/ASHRAE Standard 55R-2010—Thermal Environmental Conditions for Human Occupancy*. Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. http://www.ashrae.org/technology/page/548

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The Commercial Building Partnerships

The Commercial Buildings Partnership was developed the by U.S. Department of Energy (DOE) to assist companies and organizations that design, build, own, manage or operate portfolios of buildings. The DOE offers technical assistance and guidance on implementing energy efficient technologies to transform commercial buildings. Companies and organizations work with DOE, national laboratories, and private-sector experts (including design and technical) to achieve optimal energy savings within their budget. The goal is to achieve whole building energy savings of 30% or better in retrofits and 50% or better in new construction compared to the minimally code compliant ASHRAE Standard 90.1-2004 baseline.

DOE National Laboratories identify the best strategies for meeting energy saving goals by running performance reviews, modeling, and recommending designs that can be replicated for future projects. Collected data provides the operational and cost data needed to make a solid business case for investment in high-performance buildings. These findings will enable replication throughout building portfolios and the commercial building sector at large, strengthening the participant's position as a leader in energy conservation by influencing others in the commercial building sector.

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